Journal of Applied Biomechanics, 2015, 31, 122-127
http://dx.doi.org/10.1123/JAB.2014-0102

Human Kinetics
TECHNICAL NOTES

Surrogate Headform Accelerations Associated With Stick Checks in Girls' Lacrosse

Joseph J. Crisco, Laura Costa, Ryan Rich, Joel B. Schwartz, and Bethany Wilcox
Brown University

Girls' lacrosse is fundamentally a different sport than boys' lacrosse, and girls are not required to wear protective headgear. Recent epidemiological studies have found that stick checks are the leading cause of concussion injury in girls' lacrosse. The purpose of this study was to determine stick check speeds and estimate the head acceleration associated with direct checks to the head. In addition, we briefly examine if commercially available headgear can mitigate the accelerations. Seven (n = 7) experienced female lacrosse players checked, with varying severity, a NOSCAE and an ASTM headform. Stick speed at impact and the associated peak linear accelerations of the headform were recorded. The NOCSAE headform was fitted with four commercially available headgear and similar stick impact testing was performed. The median stick impact speed was 8.1 m/s and 777 deg/s. At these speeds, peak linear acceleration was approximately 60*g*. Three out of the four headgear significantly reduced the peak linear acceleration when compared with the bare headform. These data serve as baseline for understanding the potential mechanism and reduction of concussions from stick impacts in girls' lacrosse.

Keywords: lacrosse, female, impacts, headgear

Girls' lacrosse (female lacrosse at the youth and high school levels) is an incidental contact sport in which mouth guards and eye wear are the only mandated protective gear. The disparity between the protective gear worn by girls and by boys (helmet, shoulder pads, arm pads, and gloves) has heightened the public concerns over the risk of injury in girls' lacrosse. This heightened concern may not be warranted as there are significant differences in the rules between girls' and boys' lacrosse. Girls' lacrosse does not permit intentional stick or bodily contact, whereas the boys' sport permits such contact.

Severe traumatic brain injuries, injuries for which boys' helmets are designed to prevent, have not been recorded in girls' lacrosse to date.[1–9] Nonetheless, head protection in girls' lacrosse is a current and important topic in the nation's fastest growing sport. Informed decisions by governing bodies, coaches, and parents on protective equipment must be based on scientific evidence and currently, there is little available on head impacts in girls' lacrosse.

In girls' and women's lacrosse, stick contact to the head accounts for the majority of concussion injuries.[4,7,10,11] Our previous studies have measured collegiate stick velocities ranging from 13 m/s to 25 m/s during shooting.[12] Given the reported association of stick checks with concussion injuries, an understanding of the head accelerations associated with stick checks would provide valuable insight into the possible mechanism of these injuries.

The first objective of this study was to determine surrogate head accelerations associated with various stick checks experienced in girls' lacrosse in a laboratory setting. The second objective was to characterize the response of various commercially available protective headgear to stick checks of comparable severity.

Joseph J. Crisco, Laura Costa, Ryan Rich, Joel B. Schwartz, and Bethany Wilcox are with the Bioengineering Laboratory, Department of Orthopaedics, Warren Alpert Medical School of Brown University and Rhode Island Hospital, Providence, RI. Address author correspondence to Joseph J. Crisco at joseph_crisco@brown.edu.

Methods

Seven (n = 7) female lacrosse players (ages 12–14 years, lacrosse experience 3–7 years) participated after institutional review board approval and informed written consent. Six typical stick models from three manufacturers were used in this study. Sticks were prepared for testing by applying five 9 mm markers: two on the tip of the head (each 7.5 cm from center), one at the base of the head and one at the throat/neck; and three on the shaft (28, 30.5, and 51 cm from tip).

Two headforms were used: an ASTM International (model E, 2.550 kg; West Conshohocken, PA) headform and a National Operating Committee on Standards for Athletic Equipment (NOCSAE, size: small, 4.376 kg; Overland Park, KS) headform. Headforms were mounted to a commercially available compression spring (spring-tempered steel, 5" length, 2.7" outer diameter, 0.31" wire diameter, 175 lb/in) whose lateral bending stiffness was determined to be 1.8 N·m/deg. A rubber rod (polyurethane rubber, 1–3/4" diameter, 6" length, 60A durometer) was inserted into the spring to help dampen vibrations. A triaxial accelerometer (model 354B173, range ± 500 g; PCB Piezotronics, Depew, NY) was mounted at the center of gravity (CG) of each headform, sampled at 20 kHz and time synchronized with the motion capture data of the lacrosse stick.

Each player attempted to complete at least 36 impacts per bare headform (6 impacts for 3 headform impact locations and 2 points of stick contact) at their preferred frequency (Figure 1a). Six impacts were repeated for three locations on each headform (front, side, top) and two points of contact on the stick (throat or head/shaft juncture and the shaft [Figure 1b]). Players were instructed to check with maximal effort. Missed and glancing checks were not analyzed. The order of the stick models was selected randomly and not all models were swung by each player. Stick swings were tracked at 250 Hz using a four-camera Oqus 5-series infrared sensing system (Qualysis, Gothenburg, Sweden). No differences with stick model

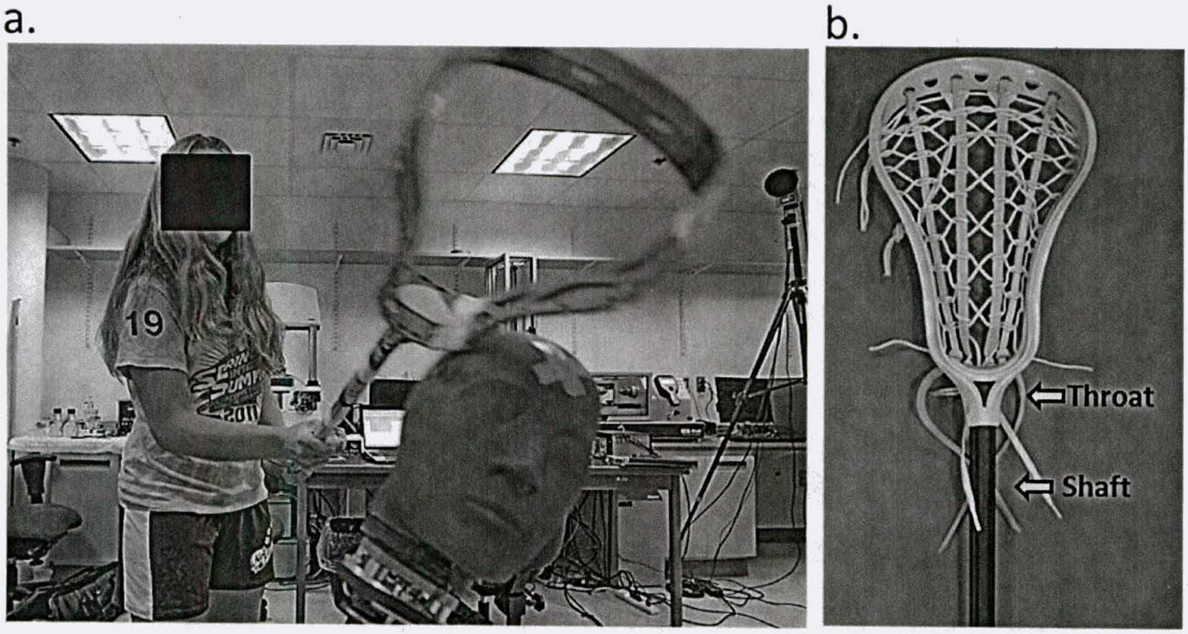

Figure 1 — A female lacrosse player (a) striking the side of the bare NOCSAE headform with the throat of a lacrosse stick. Players checked the headform with two locations (b) on the stick; the throat and the shaft.

were detected in the analysis and therefore all data was reported independent of stick model.

Resultant linear acceleration of the CG of the headform was calculated and filtered in accordance with ASTM and NOCSAE standards using a low-pass, four-pole Butterworth filter with a 1 kHz cutoff frequency. Peak linear accelerations (*g*) were identified as the maximum value. Gadd Severity Index (GSI) was calculated for each impact.[13] Stick swing linear and rotational velocity at impact were calculated using previously developed algorithms.[14]

In the second part of this study, using an identical test setup as described above, the NOCSAE headform was fitted with four types of headgear: a men's lacrosse helmet, a rugby scrum cap, mixed martial arts (MMA) headgear, and a soft headgear manufactured for use in field hockey and girls' or women's lacrosse (Table 1). A total of 20 stick impacts were delivered to the side and to the back of the headform for all headgear conditions (Figure 2) with the shaft of the stick (Figure 1b). Headform peak linear acceleration and swing speed were calculated as described above. Linear regression at 10.4 m/s (the median of swing speeds) was used to compare the peak linear acceleration of the bare headform and the four models of headgear.

Statistical Analysis

Descriptive statistics were used to describe linear and rotational stick impact speeds. Multiple linear regression was used to assess differences in headforms, headform impact location, and stick contact location as a function of stick impact speed. Differences in the mean peak linear acceleration of the four headgear were examined using a one-way ANOVA and a post hoc Dunnett's multiple comparison test with the bare headform as the control. Statistical significance was set at $\alpha = .05$ (GraphPad Prism; GraphPad Software, San Diego, CA).

Table 1 Protective headgear used in study

Sport	Model / Manufacturer
Men's lacrosse	CLH2 (SPR fit) / Cascade
Rugby	Xact / Gilbert Rugby
Mixed martial arts (MMA)	UFC OSFM / Zuffa
Soft headgear for field hockey and girls'/women's lacrosse	SG 360 / HRP sports

Results

A total of 508 impacts were successfully analyzed: 257 impacts on the ASTM headform and 251 impacts on the NOCSAE headform. The median stick impact speed was 8.1 m/s with a 25%–75% percentile range of 6.3–10.3 m/s. The median rotational stick speed at impact was 777 deg/s with a 25%–75% percentile range of 638–945 deg/s.

Peak linear accelerations of the headforms did not differ among impacts to the front, top, or side of the headform for either the throat or the shaft. This observation was supported by a multiple linear analysis of peak accelerations as a function of stick impact speed for each headform impact location, within each stick contact location (NOCSAE/shaft: $P = .327$, NOCSAE/throat: $P = .6124$, ASTM/shaft: $P = .267$, ASTM/throat: $P = .1557$). Therefore, headform impact location was grouped for subsequent analyses.

Between headforms, peak accelerations with the shaft impacts did not differ ($P = .3716$), but impacts with the throat of the stick resulted in substantially lower peak linear accelerations than with the shaft on the NOCSAE headform ($P < .0001$, Figure 3).

GSI increased nonlinearly with increasing peak linear acceleration (Figure 4). Statistically there was a significant difference

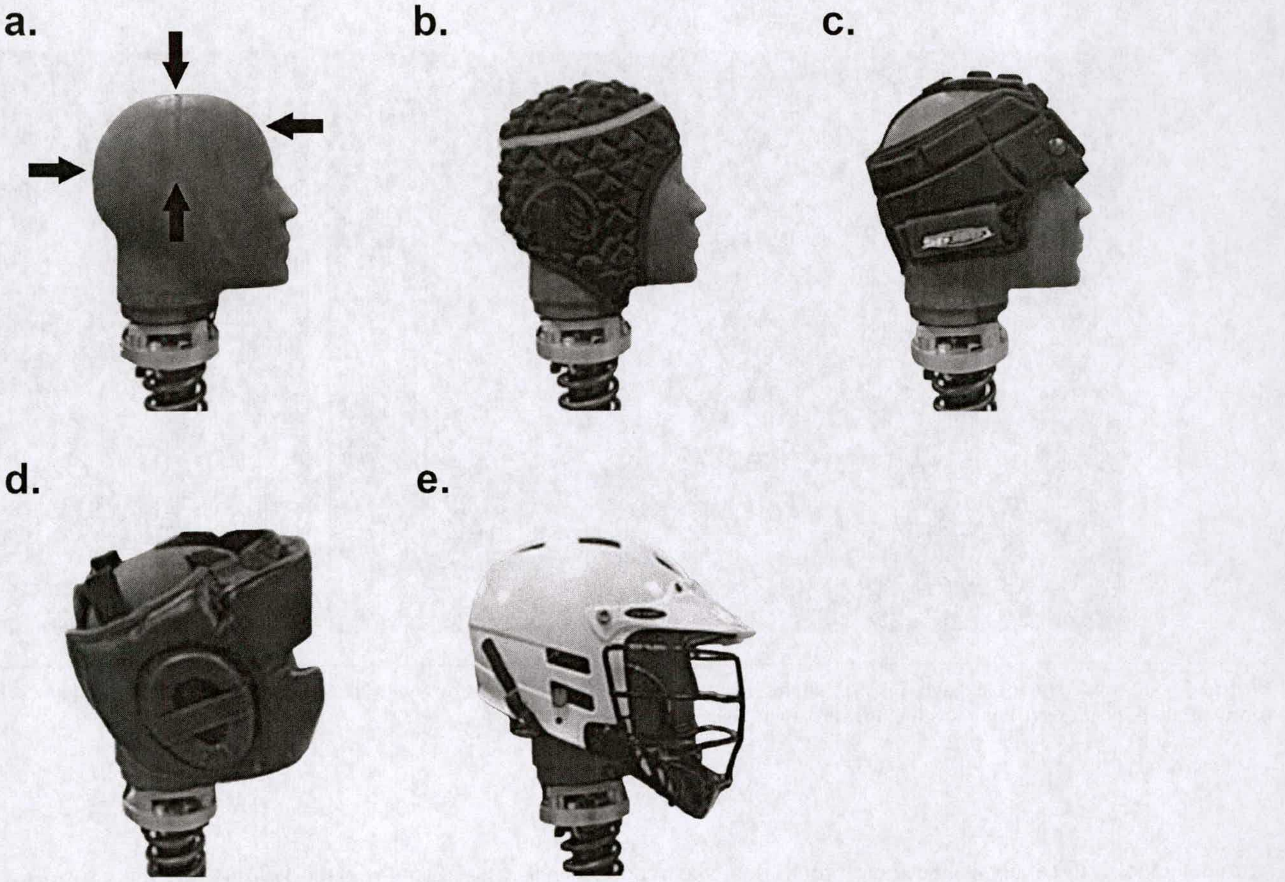

Figure 2 — NOCSAE headforms in five different headgear conditions: (a) bare; (b) rugby scrum cap; (c) soft headgear for field hockey, soccer, or lacrosse (female); (d) MMA headgear; and (e) lacrosse helmet (males). Impact locations included the front, side, top, and back of the headform (a).

($P < .001$) between the fifth order polynomial coefficients that best fit each GSI and peak acceleration relationship, but the magnitude of the difference was only approximately 20 GSI.

To evaluate the role of different headgear in mitigating stick impacts at 10.4 m/s, a total of 100 impacts to the side and back were analyzed (Table 2). The men's lacrosse helmet, MMA headgear, and field hockey and women's lacrosse soft headgear significantly ($P < .001$) reduced the peak linear accelerations in side impacts by a mean of 53.4*g*, 15.4*g*, and 18.9*g*, respectively, with respect to the bare headform. The peak acceleration associated with the rugby scrum cap was significantly increased by 11.4*g* from that of the bare NOCSAE headform. Peak accelerations of the impacts to the back were significantly ($P < .001$) reduced by a mean of 127.7*g*, 53.3*g*, 45.5*g*, and 45.9*g*, for men's lacrosse, rugby, MMA, and field hockey and women's lacrosse soft headgear.

Discussion

The objectives of this study were to determine stick check speeds and the associated head acceleration when the checks were delivered to a headform. In addition, we sought to estimate the ability of commercially available headgear to mitigate the effects of the stick checks.

Stick checks to the headforms at the average swing speed resulted in peak linear accelerations of approximately 60*g*. This is substantially lower than previously reported accelerations associated with concussions in male high school and collegiate football players (approximately 100*g*[15]), but higher than noninjurious head impacts experienced in a field study of youth girls' soccer players.[16] We also note that GSI values produced in this study are far lower than those reported for impacts associated with concussion in an on-field study of male football players (approximately 439 GSI).[15] While these comparisons are useful for placing the accelerations observed in this study into context with head accelerations experienced in other helmeted and nonhelmeted sports, data from our laboratory test may not be directly comparable to these field tests because of the various approaches to measuring on-field head acceleration and the limited biofidelity of headforms. In addition, factors that influence biomechanical tolerances to concussion injury, such as age and sex, are still not well understood.

While stick speeds in the study were substantially lower than stick speeds observed during shooting in a group of high school and collegiate male and female lacrosse players (13-25 m/s or 30–55 mph),[12] the sticks used in this study sustained substantial damage to the shafts. This damage, which is not characteristic of normal play, suggests that the stick checks in this study were unusually aggressive. Thus, the headform accelerations observed in this study most likely represent a "worst case scenario". On the field, these impacts would be blatant and egregious fouls. Despite the fact that there are several rules[17] that directly pertain to reducing the risk of head injury, including stick checks to the head, studies

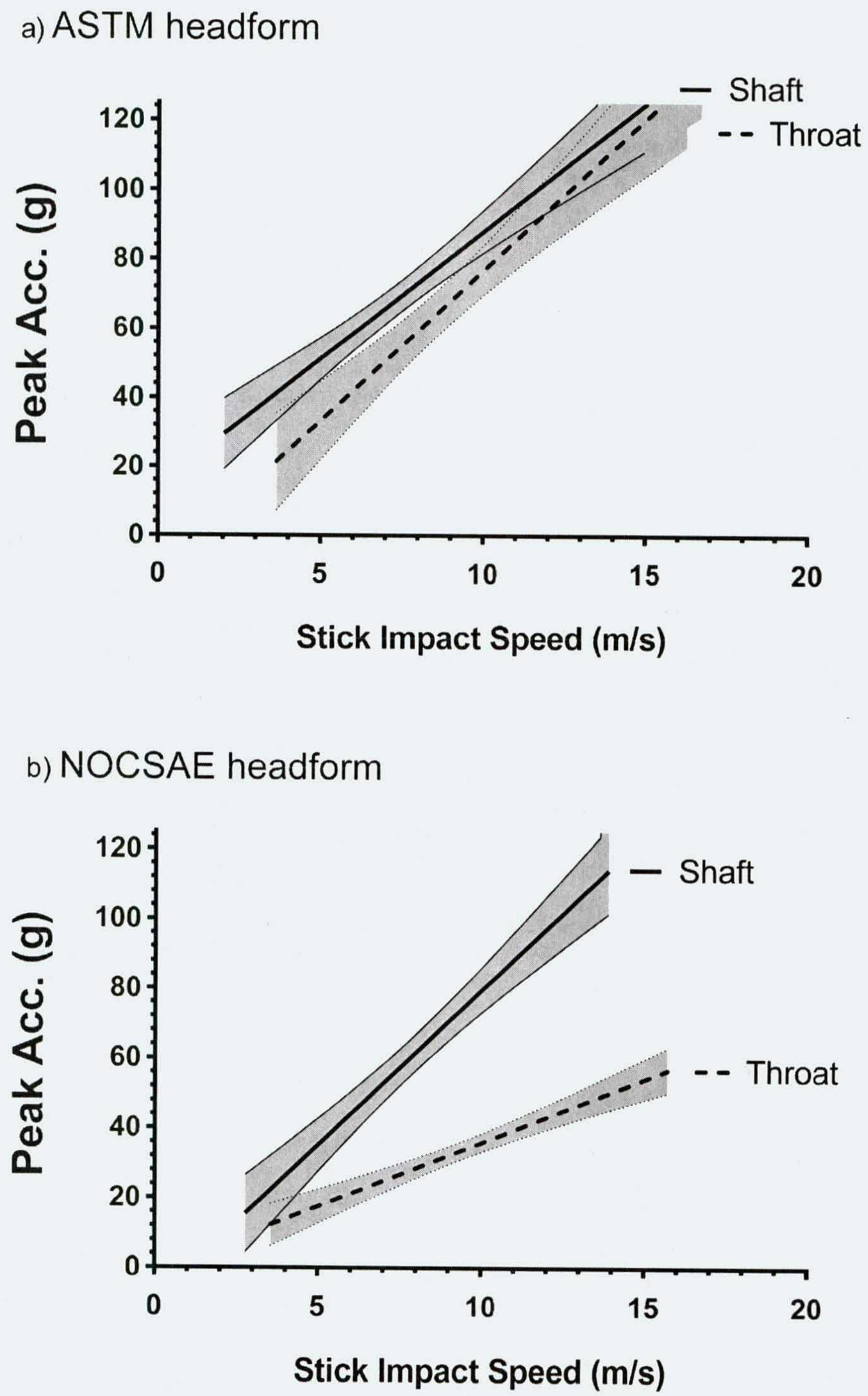

Figure 3 — ASTM (a) and NOCSAE (b) headform acceleration increased with increasing stick speed (linear regression and 95% CI). Stick contact location had no effect, except head accelerations were significantly reduced with throat impacts to the NOCSAE headform (b).

Table 2 Peak linear accelerations for bare headform and four headgear conditions interpolated at a swing speed of 10.4 m/s with 95% confidence interval (CI)

	Peak Linear Acceleration (g) (95% CI)	
Headform Condition	Side Impacts	Back Impacts
Bare NOCSAE headform	81.6 (4.6)	150.7 (6.3)
Men's lacrosse	28.2 (1.2)*	23.1 (1.6)*
Rugby	93.0 (16.6)*	97.5 (2.0)*
Mixed martial arts (MMA)	66.3 (10.9)*	105.2 (5.2)*
Soft headgear for field hockey and girls'/women's lacrosse	62.7 (3.2)*	104.8 (6.8)*

*Significantly different from the bare headform.

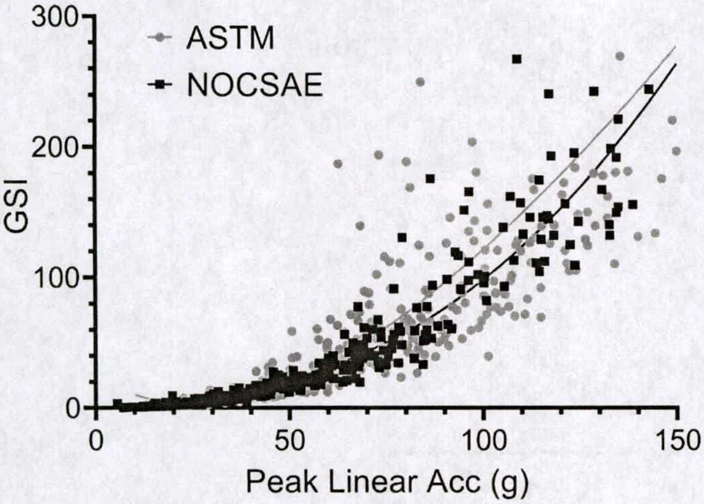

Figure 4 — GSI increased nonlinearly with peak linear acceleration and differed by approximately 20*g* between headforms.

have found that only 25% of stick-related head injuries result in a penalty.[11] While it has also been reported that the majority of head injuries in female lacrosse result from unintentional stick contact to the head,[4,7,10] appropriate enforcement of the rules plays a key role in reducing stick check head injuries.

Overall, accelerations of the ASTM headform were greater than those of the NOCSAE headform for the same stick speeds. This could be due to differences in headform construction; the ASTM is solid magnesium while the NOCSAE is a complex, multiple component silicone and urethane structure that has approximately 40% more mass. This study is limited to a few impact locations. In the bare headform testing only the top, side, and front were impacted. When we chose to examine the headgear, we added impacts to the back. While we found no differences among the top, side, and front, accelerations from back impacts were notably different than those from the side of the bare headform when testing the headgear. The complexity of the construction of the NOCSAE headform may explain these differences, as well as why stick impact location (shaft vs. throat) had a notable effect with the NOCSAE headform. The headforms were mounted on a spring construct. We designed and confirmed the lateral bending stiffness of the neck complex to be approximately 1.8 N·m/deg, which is within the range of 1.08–2.00 N·m/deg reported in previous biomechanical tests of human cervical spines.[18]

For impacts to the headgear, the largest decrease in acceleration was seen in the men's lacrosse helmet. The MMA headgear and the soft headgear had similar decreases of approximately 20% and 30% for side and back, respectively, while the mean acceleration for the rugby headgear actually increased relative to the bare headform for side impacts by 14% but decreased by 35% for back impacts. The reason for the increase is unknown, but may be associated with experimental variation or a complex mechanical interaction between the headgear and headform. The correlation of these performances with the mitigation of concussion injury remains unknown at this time because no definitive association between peak acceleration and the risk of concussion injury has been conclusively established. In addition, we note that we did not measure rotational acceleration, which is also a likely contributor to the risk of concussion injury,[19] but it has been suggested to correlate by impact location with linear acceleration.[19–21] The men's lacrosse helmet was the only headgear with a hard plastic shell. The use of hard-shelled helmets in girls' lacrosse would be a concern because female players do not wear any other protective equipment, and the hard shell and facemask may increase the rate of injuries to other players. Currently, soft headgear is permitted for female lacrosse players.[17] Presently, a debate on whether to mandate female lacrosse players to wear headgear exists. It is unknown if headgear would reduce the risk of head injury in girls' lacrosse. Some observers contend that the introduction of headgear to girls' lacrosse would increase aggressive play thus leading to higher rates of injury.[7,22] This phenomenon, an increase in the recklessness of play based on a misguided belief of protection from injury with additional equipment, is known as risk compensation or the "Peltzman effect", and it has been analyzed in a variety of sports.[23,24]

This study did not evaluate ball impacts, which are the second leading cause of concussion in girls' lacrosse.[4,7,10,11] Lacrosse balls weigh approximately half of what a lacrosse stick weighs (< 6 oz.) and travel at roughly the same speeds as the stick shot,[4,7,10,11] so the values reported here likely capture the impact severity associated with ball contact. Rotational acceleration was not measured, but given that the impacts were delivered primarily through the CG, we postulate that linear acceleration is a valid measure of the severity of the impact.

There is an inherent risk of injury in any sport. Understanding head impact exposure for individual athletes and the impact response of currently available protective equipment to comparable impacts is an important first step in understanding preventative strategies for head injuries. These data should assist governing and rulemaking bodies in making informed decisions related to protective headgear in girls' lacrosse.

Acknowledgments

Funding was provided by US Lacrosse and the National Operating Committee on Standards for Athletic Equipment (NOCSAE). The opinions expressed in this manuscript are solely those of the authors and do not necessarily reflect those of US Lacrosse or NOCSAE.

References

1. Goldenberg MS, Hossler PH. Head and facial injuries in interscholastic women's lacrosse. *J Athl Train*. 1995;30(1):37–41. PubMed
2. Webster DA, Bayliss GV, Spadaro JA. Head and face injuries in scholastic women's lacrosse with and without eyewear. *Med Sci Sports Exerc*. 1999;31:938–941. PubMed doi:10.1097/00005768-199907000-00004
3. Matz SO, Nibbelink G. Injuries in intercollegiate women's lacrosse. *Am J Sports Med*. 2004;32(3):608–611. PubMed doi:10.1177/0363546503262172
4. Hinton RY, Lincoln AE, Almquist JL, Douoguih WA, Sharma KM. Epidemiology of lacrosse injuries in high school-aged girls and boys: a 3-year prospective study. *Am J Sports Med*. 2005;33:1305–1314. PubMed doi:10.1177/0363546504274148
5. Luckstead EF, Patel DR. Catastrophic pediatric sports injuries. *Pediatr Clin North Am*. 2002;49:581–591. PubMed doi:10.1016/S0031-3955(02)00006-8
6. Covassin T, Swanik CB, Sachs ML. Epidemiological considerations of concussions among intercollegiate athletes. *Appl Neuropsychol*. 2003;10:12–22. PubMed doi:10.1207/S15324826AN1001_3
7. Lincoln AE, Hinton RY, Almquist JL, Lager SL, Dick RW. Head, face, and eye injuries in scholastic and collegiate lacrosse: a 4-year

prospective study. *Am J Sports Med*. 2007;35(2):207–215. PubMed doi:10.1177/0363546506293900

8. Otago L, Adamcewicz E, Eime R, Maher S. The epidemiology of head, face and eye injuries to female lacrosse players in Australia. *Int J Inj Contr Saf Promot*. 2007;14(4):259–261. PubMed doi:10.1080/17457300701602381
9. Diamond PT, Gale SD. Head injuries in men's and women's lacrosse: a 10 year analysis of the NEISS database. National Electronic Injury Surveillance System. *Brain Inj*. 2001;15(6):537–544. PubMed doi:10.1080/02699050010007362
10. Dick R, Lincoln AE, Agel J, Carter EA, Marshall SW, Hinton RY. Descriptive epidemiology of collegiate women's lacrosse injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. *J Athl Train*. 2007;42(2):262–269. PubMed
11. Caswell SV, Lincoln AE, Almquist JL, Dunn RE, Hinton RY. Video incident analysis of head injuries in high school girls' lacrosse. *Am J Sports Med*. 2012;40(4):756–762. PubMed doi:10.1177/0363546512436647
12. Crisco JJ, Rainbow MJ, Wang E. Modeling the lacrosse stick as a rigid body underestimates shot ball speeds. *J Appl Biomech*. 2009;25(2):184–191. PubMed
13. Gadd C. Use of a Weighted-Impulse Criterion for Estimating Injury Hazard. Presented at: *SAE* 10th Stapp Conference (SAE Paper# 660793):164–174.
14. Crisco JJ, Greenwald RM, Blume JD, Penna LH. Batting performance of wood and metal baseball bats. *Med Sci Sports Exerc*. 2002;34(10):1675–1684. PubMed doi:10.1097/00005768-200210000-00021
15. Beckwith JG, Greenwald RM, Chu JJ, et al. Head impact exposure sustained by football players on days of diagnosed concussion. *Med Sci Sports Exerc*. 2013;45(4):737–746. PubMed doi:10.1249/MSS.0b013e3182792ed7
16. Hanlon EM, Bir CA. Real-time head acceleration measurement in girls' youth soccer. *Med Sci Sports Exerc*. 2012;44(6):1102–1108. PubMed doi:10.1249/MSS.0b013e3182444d7d
17. US Lacrosse. *Official Rules for Girls and Women's Lacrosse*. Baltimore, MD: US Lacrosse; 2010.
18. Voo LM, Pintar FA, Yoganandan N, Liu YK. Static and dynamic bending responses of the human cervical spine. *J Biomech Eng*. 1998;120(6):693–696. PubMed doi:10.1115/1.2834880
19. Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF. Concussion in professional football: reconstruction of game impacts and injuries. *Neurosurgery*. 2003;53:799–812, discussion 812–814. PubMed
20. Viano DC, Withnall C, Halstead D. Impact performance of modern football helmets. *Ann Biomed Eng*. 2012;40(1):160–174. PubMed doi:10.1007/s10439-011-0384-4
21. Rowson S, Duma SM, Beckwith JG, et al. Rotational head kinematics in football impacts: an injury risk function for concussion. *Ann Biomed Eng*. 2012;40(1):1–13. PubMed doi:10.1007/s10439-011-0392-4
22. Schwarz A. A case against helmets in lacrosse. *NY Times* 2011;16. Available at: http://mysite.cherokee.k12.ga.us/personal/jennifer_jackson/site/Lists/Subject%202%20Calendar/Attachments/67/A%20Case%20Against%20Helmets%20in%20Lacrosse.docx. Accessed May 10, 2014.
23. Hagel B, Meeuwisse W. Risk compensation: a "side effect" of sport injury prevention? *Clin J Sport Med*. 2004;14(4):193–196. PubMed doi:10.1097/00042752-200407000-00001
24. Chong A, Restrepo P. *Peltzman on Ice: Evidence on Compensating Behavior Using a Natural Experiment from Ice Hockey*. The George Washington University, Institute for International Economic Policy; 2011. Available at: http://ideas.repec.org/p/gwi/wpaper/2011-12.html. Accessed May 10, 2014.